

Making Baryons Below the Electroweak Scale

Mark Trodden

Physics Department, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH

44106-7079, USA

E-mail: trodden@huxley.cwru.edu

Abstract

I describe a new way for baryogenesis to proceed, which evades many of the problems of GUT and electroweak scenarios. If the reheat temperature after inflation is below the electroweak scale, neither GUT baryon production nor traditional electroweak baryogenesis can occur. However, non-thermal production of sphaleron configurations via preheating could generate the observed baryon asymmetry of the universe. Such low scale baryon production is particularly attractive since it evades a number of strong constraints on reheating from gravitino and moduli production.

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I. INTRODUCTION

Over the past twenty to thirty years, a variety of microphysical explanations for the observed baryon asymmetry of the universe have been proposed. Initially, Grand Unified Theories (GUTs), which easily satisfy Sakharov's three criteria for baryogenesis, were demonstrated to be able to account for the observed baryon to photon ratio in the Universe today [1]. Although proton decay experiments soon ruled out the simplest theories, GUT baryogenesis remained a viable possibility in more complicated models. However, GUTs also lead to several cosmological problems. Since inflation erases any preexisting asymmetry, GUT baryogenesis is only possible if the reheating scale following inflation is large. It has been realized for some time that this raises the possibility of unacceptable defect and, in supersymmetric (SUSY) models, gravitino and moduli, production after inflation [2]. However, as we've heard in a number of talks here [3], these concerns have become much more pressing recently, with the realization that, in the context of preheating, gravitino and moduli production can be so efficient as to constrain the reheat temperature to be less than 10 GeV in some models.

An additional problem for GUT baryogenesis contained the seeds for potentially viable baryogenesis at the much lower electroweak scale ($\sim 10^2$ GeV). Coherent configurations of electroweak gauge and Higgs fields, first pointed out by 't Hooft [4], can violate baryon number via non-perturbative physics. At zero temperature this effect is exponentially suppressed by the energy of a field configuration called the *sphaleron*, and is essentially irrelevant. However, as pointed out by Kuzmin, Rubakov and Shaposhnikov [5], and later discussed by Arnold and McLerran [6], at finite temperature, sphaleron production and decay can be rampant. This has the virtue of allowing copious baryon number violation, but can also be a curse. If the universe remains in thermal equilibrium until sphaleron production ceases, the net effect of these processes will be to drive the baryon number of the universe to zero, unless careful precautions are made to ensure either out of equilibrium sphaleron decay, or quantum number restrictions which forbid the elimination of the net baryon number. In the light of recent lattice and experimental data, this seems to require new fields at the weak scale, perhaps those predicted by SUSY.

Finally, once again, if the gravitino reheating constraint is sufficiently strong, we can not allow the universe to reheat to a sufficient temperature to allow even electroweak baryogenesis to take place.

Thus, thermal sphaleron production creates both challenges and opportunities for the generation of the baryon asymmetry. While it can wipe out any baryon number generated at the GUT scale, it offers the possibility of electroweak baryogenesis, although in practice this is quite difficult to achieve (for reviews see [7]).

As I alluded to earlier, *reheating* after cosmological inflation has been carefully rethought over the last few years. Studies of the inflaton dynamics have revealed the possibility of a period of parametric resonance, prior to the usual scenario of energy transfer from the inflaton to other fields. This phenomenon, which is characterized by large amplitude, non-thermal excitations in both the inflaton and coupled fields, has become known as *preheating* [8,9]. Two particularly interesting consequences of this are the strict graviton and moduli constraints that result [3], and the idea that topological defects may be produced after inflation even when the final reheat temperature is lower than the symmetry breaking scale of the defects [8,10–12].

In this article, I describe how all these ideas can be combined to yield a viable and attractive model which obviates many of the problems with both standard GUT, and electroweak baryogenesis [13]. In particular, I show how baryogenesis might still occur, even if inflation ends with reheating below the electroweak scale.

II. THE BASIC MECHANISM

The fundamental idea is that, if topological defects can be produced non-thermally during preheating, then so can coherent configurations of gauge and Higgs fields, carrying nontrivial values of the Higgs winding number

$$N_H(t) = \frac{1}{24\pi^2} \int d^3x \epsilon^{ijk} \text{Tr}[U^\dagger \partial_i U U^\dagger \partial_j U U^\dagger \partial_k U] . \quad (1)$$

In this parameterization, the $SU(2)$ Higgs field Φ has been expressed as $\Phi = (\sigma/\sqrt{2})U$, where $\sigma^2 = 2(\varphi_1^* \varphi_1 + \varphi_2^* \varphi_2) = \text{Tr}\Phi^\dagger \Phi$, and U is an $SU(2)$ -valued matrix that is uniquely defined anywhere σ is nonzero.

These winding configurations are not stable and evolve to a vacuum configuration plus radiation. In the process fermions may be anomalously produced. If the fields relax to the vacuum by changing the Higgs winding then there is no anomalous fermion number production. However, if there is no net change in Higgs winding during the evolution (for example σ never vanishes) then there is anomalous fermion number production. Since winding configurations will be produced out of equilibrium (by the nature of preheating) and since

CP-violation affects how they unwind, all the ingredients to produce a baryonic asymmetry are present (see [14] for a detailed discussion of the dynamics of winding configurations).

If the final reheat temperature is lower than the electroweak scale, then the production of small-scale winding configurations by resonant effects is analogous to the production of local topological defects. In fact, the configurations that are of interest can be thought of as *gauged textures*.

Given this connection, a rough underestimate of the number density of winding configurations may be obtained by counting defects in recent numerical simulations of defect formation during preheating [10], while keeping in mind that the important case is when the symmetry breaking order parameter is not the inflaton itself, but is the electroweak $SU(2)$ Higgs field, and is coupled to the inflaton. The relevant quantity is the number density of defects directly after preheating, since winding-anti-winding pairs of configurations will not typically have time to find each other and annihilate before they decay. Finally, since the Higgs winding is the only non-trivial winding present at the electroweak scale, it is reasonable to assume that any estimates of defect production in general models can be quantitatively carried over to estimate of the relevant Higgs windings for preheating at the electroweak scale.

III. A (TOO?) SIMPLE EXAMPLE

Before I make an estimate of the baryon asymmetry from this mechanism, I'll provide an example of a toy model which satisfies all the relevant constraints.

Consider the potential

$$V(\phi, \chi) = \frac{1}{2}m^2\phi^2 + \frac{1}{2}g^2\phi^2\chi^2 + \frac{1}{4}\lambda(\chi^2 - \chi_0^2)^2, \quad (2)$$

for an inflaton ϕ , coupled to the electroweak Higgs field χ .¹ Here $\chi_0 = 246$ GeV is the electroweak symmetry breaking scale, m is the (false vacuum) inflaton mass, and λ (the Higgs self-coupling, here assumed to be of order unity) and g are dimensionless constants.

The mechanism only works if parametric resonance into electroweak fields occurs in this model. The condition for this to happen is [17]

¹This model has also been independently proposed in a similar context in [15], and for a description of this see Misha Shaposhnikov's contribution to these proceedings [16]

$$q = \frac{g^2 \phi_0^2}{2m_\phi^2} > 10^3 , \quad (3)$$

where ϕ_0 is the value of ϕ at the end of inflation. For the values quoted here, this condition yields $g < 10^{-2}$ (I'll take $g \sim 10^{-2}$). It is important that the temperature fluctuations in the cosmic microwave background (CMB), given by

$$\frac{\delta T}{T} \sim g \frac{\chi_0^5}{M_p^3 m^2} , \quad (4)$$

for the values I've chosen here, are of the correct magnitude. Clearly this is satisfied by the choice $m \sim 10^{-21}$ GeV. Finally, since the reheat temperature in this model is roughly bounded by $T_{RH} \leq (m\phi_0)^{1/2}$, the requirement that any baryons produced not be erased by equilibrium sphaleron processes is also satisfied.

This is not a particularly natural toy model, and in fact, it may develop problems if we go beyond tree level [18]. However, the point of this example is merely to provide an existence proof which makes explicit the constraints on such a possibility.

IV. CALCULATING THE ASYMMETRY

Consideration of topological defect production following inflation has been discussed by several authors [11,12]. For definiteness, let us focus on the results of Khlebnikov *et al.*. These show that, for sufficiently low symmetry breaking scales, the *initial* number density of defects produced is very high. Here, by initial, I mean the number seen after copious symmetry-restoring transitions cease. One may perform an estimate from the first frame of Figure 6. of reference [10]. The box size has physical size $L_{phys} \sim 50\eta^{-1}$ where η is the symmetry breaking scale, and I've assumed couplings of order unity. In this box there are of order $N = 50$ defects at early times. Thus, a rough estimate of the number density of winding configurations is

$$n_{\text{configs}} \sim \frac{N}{L_{phys}^3} \sim 4 \times 10^{-4} \eta^3 . \quad (5)$$

In order to make a simple estimate of the baryon number produced, it remains to show how CP-violation may bias the decays of these configurations to create a net baryon excess.

The effect of CP-violation on winding configurations can be very complicated, and in general depends strongly on the shapes of the configurations [14] and the particular type

of CP-violation. However, in general, the situation considered here, when out of equilibrium configurations are produced in a background low-temperature electroweak plasma most closely resembles local electroweak baryogenesis in the “thin-wall” regime. Winding configurations are produced when non-thermal oscillations take place in a region of space and restore the symmetry there. Since the reheat temperature is lower than the electroweak scale, as the region reverts rapidly to the low temperature phase, the winding configuration is left behind. In the absence of CP-violation in the coupling of the inflaton to the standard model fields, a CP-symmetric ensemble of configurations with $N_H = +1$ and $N_H = -1$ will be produced. (i.e. the probability for finding a particular $N_H = +1$ configuration in the ensemble is equal to that for finding its CP-conjugate $N_H = -1$ configuration.) Then, without electroweak CP-violation, for every $N_H = +1$ configuration which relaxes in a baryon producing fashion there is an $N_H = -1$ configuration which produces anti-baryons, and no net baryogenesis occurs. However, with CP-violation there will be some configurations which produce baryons whose CP-conjugate configurations relax without violating baryon number.

While an analytic computation of the effect of CP-violation does not exist [14], there exist numerical simulations (e.g. [19]), from which one expects that the asymmetry in the number density of decaying winding configurations should be proportional to a dimensionless number, ϵ , parameterizing the strength of the source of CP-violation. Now, at the electroweak scale the entropy density is $s \simeq 2\pi^2 g_* T^3/45$, where $g_* \sim 100$ is the effective number of massless degrees of freedom at that scale. Thus, the final baryon to entropy ratio generated is

$$\eta \equiv \frac{n_B}{s} \sim \epsilon g_*^{-1} \frac{n_{\text{configs}}}{T_{RH}^3} . \quad (6)$$

Plugging in the approximate numbers obtained earlier, this yields

$$\eta \equiv \sim 10^{-6} \epsilon . \quad (7)$$

This is the final estimate.

This estimate is quite rough, and the explicit model presented is merely a toy model. However these suggest that the mechanism proposed here could viably result in a phenomenologically allowed value of $\eta \sim 10^{-10}$, with CP violating physics within the range predicted in SUSY models for example.

V. CONCLUSIONS

I have described a new mechanism for baryogenesis, that is effective below the electroweak scale. The primary advantages of such a mechanism are that no thermal sphaleron production subsequently takes place to wash out any baryon number that is produced, and that no excess production of gravitinos or monopoles occurs, evading a very strong (although model-dependent) constraint. A more complete analysis of the mechanism requires a numerical solution to the coupled $SU(2)$ -inflaton equations of motion, in the presence of CP-violation.

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